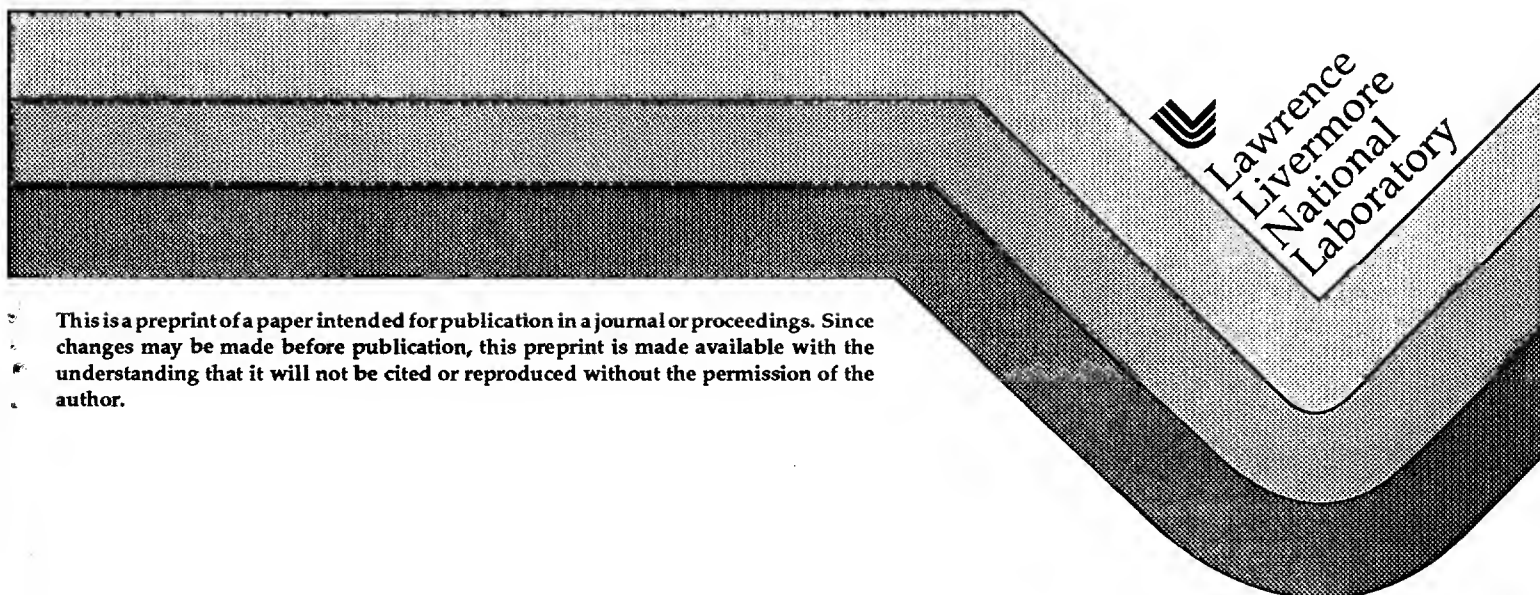


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Metallurgical Examination of Recovered Copper Jet Particles

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ABSTRACT

A shaped charge (81 mm, 42°, OFHC copper cone) was fired into a "soft" recovery bunker to allow metallurgical examination of recovered jet particles and the slug. The initial weight of the copper liner was 245 gm, of which 184 gm was recovered. The number of jet particles recovered was 37 (approximately 63% of the particles formed by the charge). Extensive metallurgical analyses were performed on the recovered slug and jet particles. The microstructural features associated with voids, e.g. dendritic grain growth, clearly indicate that the regions in the vicinity of the centerline of the slug and jet particles were melted. In this work we present calculations of jet temperature as a function of constitutive behavior. In order to predict melt in the center region of the jet we find it necessary to scale flow stress with a pressure dependent shear modulus.

1. INTRODUCTION

The fundamental metallurgical and physical parameters which affect the elongation of shaped charge jets (after jet formation) are, to a large extent, unknown. Some metallurgical effects have been demonstrated; for example, some impurity contents can lead to very brittle and particulated breakup [1-4]. Several studies have focused on breakup analyses from a mechanics viewpoint (addressing the ductile necking process from a continuum point of view) and have suggested that breakup is affected by the jet's constitutive behavior and/or radial inertia [5-7]. Also, initial perturbations in the jet caused by fluctuations in the jet formation process are believed to effect jet ductility [8]. In a recent study, it has also been shown that changes in the concentration of sulfur at grain boundaries can affect the ductile necking process [9]. Jet recovery attempts and metallurgical analyses [10,11] are useful in the progress being made in understanding the phenomena associated with jet melting [12] and associated stretching processes [13].

In this work we present metallurgical examinations of "soft recovered" copper jet particles and slug that indicate a central region of approximately 10% of the jet's diameter was molten. We also present calculations of jet temperature which are in good agreement with both the indications of a melted region presented in this work and external jet temperature measurements presented in other work.

2. "SOFT" RECOVERY EXPERIMENT

A shaped charge (81 mm, 42°, OFHC copper cone) was fired into a "soft" recovery bunker to allow metallurgical examination of recovered jet particles and the slug. The soft recovery setup had a 1.2 m by 1.2 m cross-section and consisted of 1.6 m of air, 1.8 m of shaving cream, 9 m of styrofoam with graded density, and 3.6 m of water, as shown in Figure 1. The shaving cream was contained in a box with plywood sides and plastic faces. Plywood was placed around the bottom and sides of the styrofoam to provide evidence of any particle which may have exited the recovery media. The water was used as a backstop,

with the intent to capture all particles in the preceding foam. In the actual test, one jet particle was recovered in the water. No particles were found to penetrate the plywood. The initial weight of the copper liner was 245 gm, of which 184 gm was recovered. The typical number of jet particles produced by the shaped charge that was fired is approximately 59, as determined by flash radiographs. The number of jet particles recovered was 37, or approximately 63% of the particles.

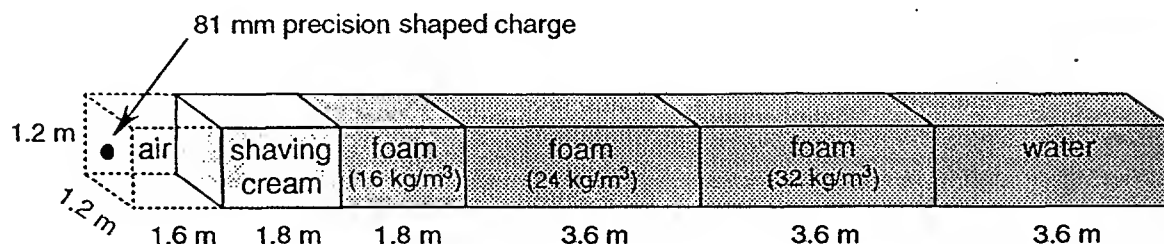


Figure 1. Shaped charge jet "soft" recovery test setup.

3. METALLOGRAPHIC EXAMINATIONS

Extensive metallurgical analyses (optical light microscopy and scanning electron microscopy (SEM)) were performed on the recovered slug and jet particles. The preparation of metallographic samples was as follows: the recovered objects were sectioned longitudinally so that the observed surface corresponded roughly to the center plane; the samples were then polished and subsequently etched with ammonium persulfate.

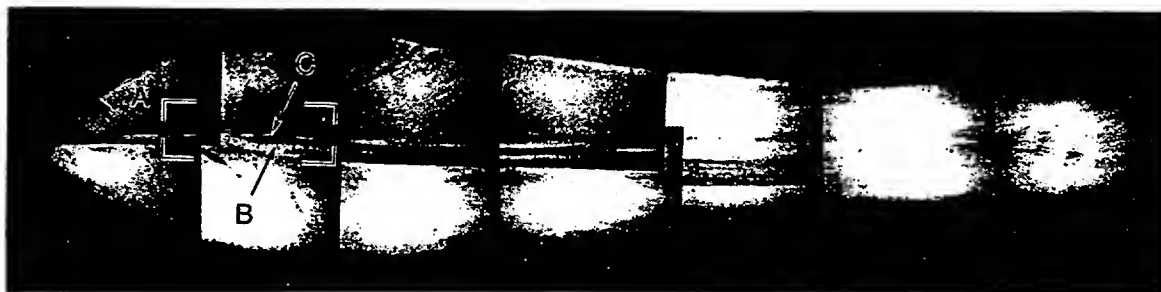


Figure 2. Low magnification photograph of the "soft" recovered slug. A central void region is located where convergence occurred during jet formation (A). High magnification photographs of the features at points B and C are shown in Figures 3 and 4, respectively.

3.1 Slug

The microstructural features associated with voids in the vicinity of the convergence zone in the slug, as shown in Figure 2, clearly indicate that this region was molten at some point. Dendritic grain structure adjacent to the void region in the slug (Figure 3) indicates that this area in the slug was melted and cooling occurred relatively slowly, producing a columnar grain structure. Also, spherical particles are observed in the void (Figure 4) which is consistent with solidification of molten material. Some areas of the voids in the slug were covered with a slag (Figure 5) which in general had a smooth modeled appearance. This by itself is a clear indication that this region was molten. The slag also had many small cracks which suggests the slag was brittle and possibly an intermetallic compound.



Figure 3. Micrograph of material adjacent to the void region in the slug showing dendritic grain structure (point B in Figure 2). This indicates that this area in the slug was melted and cooling occurred relatively slowly, producing a columnar grain structure.

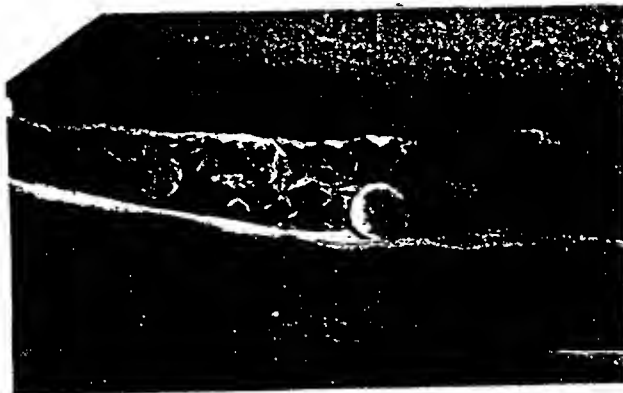


Figure 4. Spherical Particles (point C in Figure 2) in the void also indicate that this region was melted.



Figure 5. A portion of the surface of the void region in the slug is covered with a slag which has numerous cracks.

3.2 Jet Particles

Metallurgical analyses were performed on most of the larger recovered jet particles. An optical light micrograph of a recovered particle showing void regions running approximately down the center is shown in Figure 6. A scanning electron microscope photograph of an area of one of the central voids in a recovered jet particle is shown in Figure 7. This micrograph reveals the porous nature of the void and also surface features which are modeled and spherical in nature. These types of voids were typical in many of the recovered particles and suggest that a region approximately equal to 10% of the jet diameter was molten. The series of elliptical voids observed in the neck region may be associated with the tensile failure (necking) that occurred during jet elongation.

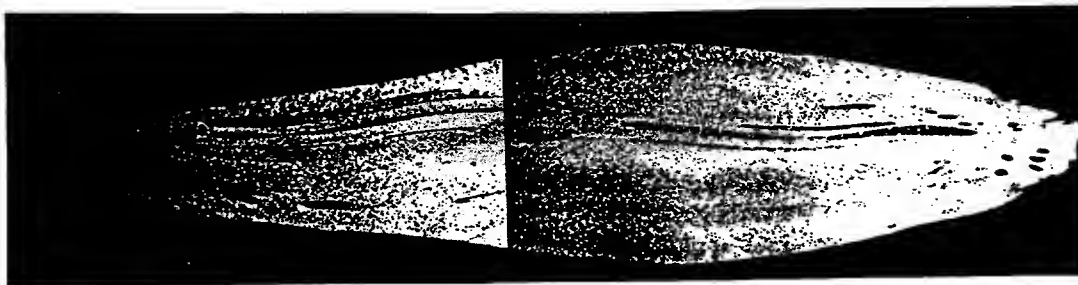


Figure 6. Micrograph of a recovered particle showing void regions running approximately down the center. A series of elliptical voids that are observed in the neck region may be associated with the tensile failure.

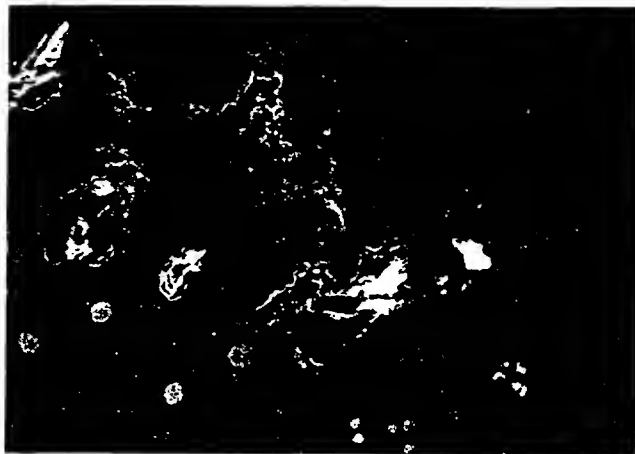


Figure 7. Scanning electron microscope photograph of an area of one of the central voids in a recovered jet particle revealing the porous nature of the void and also surface features which are spherical in nature.

4. CALCULATION OF JET TEMPERATURE

In a work by Nikkel and Lassila [14] the temperature at one location in a shaped charge jet was calculated. The methodology employed involved the use of strain and pressure histories determined by an explicit Eulerian computer code simulation of a shaped charge (which was relatively insensitive to the material strength model). A computer program called "JET" was then used to solve the equations which specified the problem, e.g. the equation of state, a strength model and a temperature dependent specific heat. It was determined that the pressure dependence of the shear modulus had a dominant effect on strength because of the very high pressures and shear deformations which occur in the convergence zone.

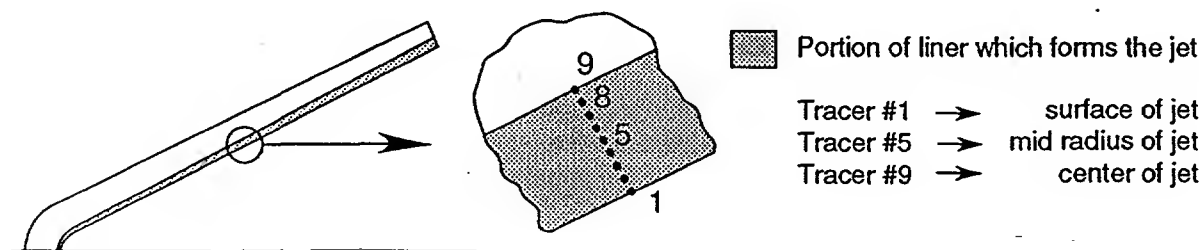


Figure 8. Cross-section of a liner showing the tracer particle locations.

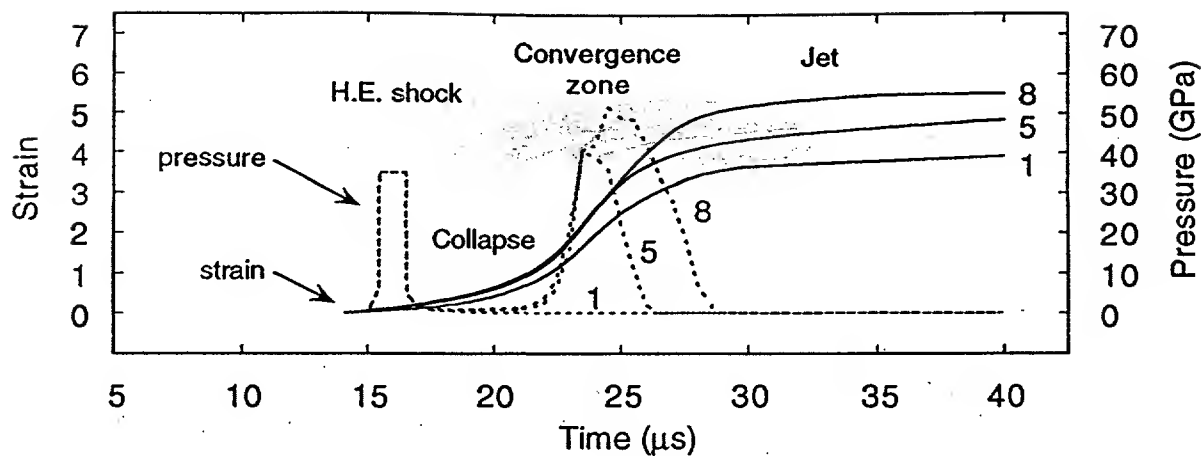


Figure 9. Strain and Pressure histories from tracer particles 1, 5, and 8.

In this work we use the same methodology described above to predict the temperature profile through the thickness of a jet at approximately the midpoint along the length. A computer simulation of a BRL precision shaped charge was performed using CALE [15] which is an arbitrary Lagrangian-Eulerian computer code. A total of nine tracer particles were used to determine strain and pressure histories. The tracer particle locations are shown in Figure 8. Representative tracer particle strain and pressure histories are shown in Figure 9.

The Mechanical Threshold Stress (MTS) material model as given in reference [16] was used in the calculation with and without a pressure dependent shear modulus. The pressure dependence of the shear modulus used is that formulated by Steinberg and Guinan [17]. The stress-strain response determined for tracer 5, shown in Figure 10, indicates substantially higher flow stresses when a pressure dependent shear modulus is used in the calculation.

The temperatures calculated, using a pressure dependent modulus, for all of the tracers are shown in Figure 11. The temperature profile for the jet is shown in Figure 12 and with some interpolation indicates that approximately 13% of the jet is melted, which is in good agreement with the indication of melt in the recovered jet particles. Also, the predicted temperature of the exterior of the jet, 580° C, is in reasonable agreement with the jet temperature measurements of von Holle and Trimble [18].

The temperature histories calculated without a pressure dependent shear modulus for tracer particles with high peak pressures in the convergence zone are substantially lower and melt is not close to being predicted. The temperature history for particle 5 calculated without a pressure dependent shear modulus (Figure 11) indicates a jet temperature 243° C below that calculated with pressure dependence.

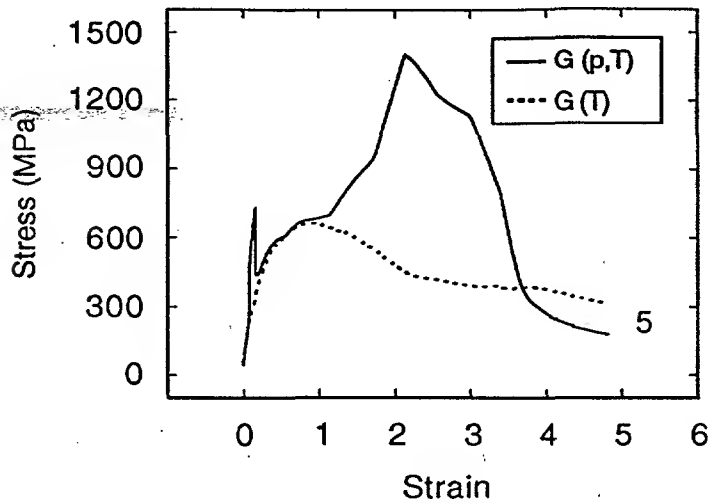


Figure 10. Calculated stress-strain response with and without a pressure dependent shear modulus for particle number 5.

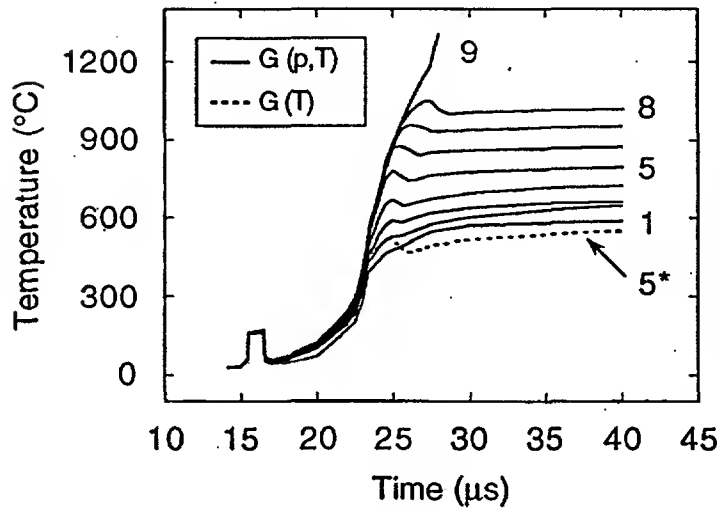


Figure 11. The calculated temperature histories of the nine tracer particles shown in Figure 8. The calculated temperature history of particle number 5 without a pressure dependent shear modulus is also shown (5*).

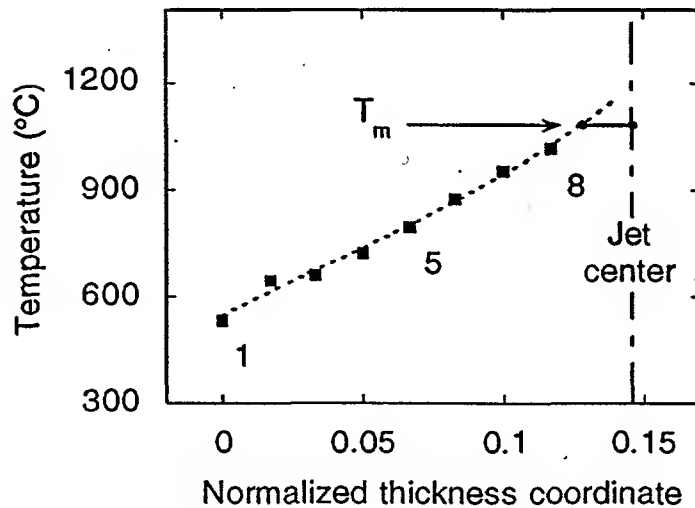


Figure 12. Variation of the final temperature from the outer surface to the center line of the jet. The normalized thickness coordinate is the distance from the outer surface divided by the original thickness of the liner.

5. SUMMARY

A successful "soft" recovery of a shaped charge jet and slug was performed. The metallurgical analyses (optical light microscopy, SEM) performed on the recovered slug and jet particles indicate that the regions in the vicinity of the centerline of the slug and jet particles were melted. Our calculations of jet temperature as a function of constitutive

behavior are in reasonable agreement with the indications of a melted region if a pressure dependent shear modulus is incorporated in the constitutive model for the liner material. The surface temperature of the jet was calculated to be 580° C, which is in reasonable agreement with copper shaped charge jet surface temperature measurements.

ACKNOWLEDGMENTS

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